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Ripple Tank Studies of the Motion of Surface Gravity-Waves

By

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INTRODUCTION

Ocean waves are generated by the action of wind blowing over the surface of water. The winds are irregular in their intensity, direction and duration and the resultant waves vary in period, height and direction of travel. When we consider also the extreme difficulties one encounters in measuring the waves in nature, and the effect of hydrography on wave characteristics, then it can be appreciated how greatly the investigator is handicapped in his study of wave action and how much model studies are needed in many instances in order to understand the basic laws of wave motion. One of the most useful units to the engineer in this regard is the ripple tank, which as a laboratory instrument permits the study of wave problems involving refraction, diffraction, reflection and decay of waves. It is also reliable and handy for demonstration purposes, for it shows, within the field of vision of an engineer, phenomena which in the prototype might cover many square miles.

EQUIPMENT

Ripple Tank:

The ripple tank used in this study is located in the Fluid Mechanics Laboratory of the University of California, Berkeley, California (Fig. 1). It is 44½ inches wide, 20 feet long, and 5 inches deep. The tank is made of aluminum, except the middle section of the bottom which consists of a glass plate, 3/8 inches thick, for observation. A point source light consisting of a 250W mercury-vapor lamp is located underneath the channel at an optical distance of approximately 10 feet. A mirror set at 45° to the horizontal reflects the light 90° to an observation screen. A schematic diagram of the ripple tank is shown in Figure 2.

The screen consisted of a piece of tracing paper stretched to a 60 inch by 60 inch wooden frame. It was located directly over the glass section of the ripple tank between two guides (one on each side of the tank) and could be raised or lowered by means of strings and pulleys for the purpose of focusing the wave images on the screen. The theory of the optical system is based on the fact that when light passes through a disturbed water surface, it will not be uniform in intensity due to the varying angle of refraction at the surface. A wave acts as a lens and concentrates light at the wave crests; hence the wave crests are represented by bright bands in the photographs.

Photographic Equipment:

The camera used was a Bell and Howell "Filmo" 16 mm movie camera 70-DA f. 1.5 with a 15mm focal length lens. The film used was Cine-Kodak Super XX high speed panchromatic safety film. Most of the motion pictures were taken at 64 frames per second (corresponding to an exposure time of 1/125 sec.) with an opening of f. 1.5. The distance between still-water level and the screen varied from 25 inches to 60 inches, averaging 40 inches. The distance between the screen and camera averaged 6 feet, in most cases. All the data observed during the tests are presented in Table I.

Wave Generator:

A plunger type wave generator was used. The generator was supported by a movable frame and could be placed at any position along the ripple tank. The amplitude of the movement was controlled by an eccentric and could be varied from 0 to about 3/4 of an inch. The frequency of the plunger could be varied from about 1 to 20 per second. By trial a wave steepness was selected so as to produce a series of clear images on the screen.

Test Conditions:

A pictorial summary of this study of wave motion in various idealized conditions is presented in Figures 3a through 3g. The various phenomena presented in these figures and the test conditions are summarized in Table I.

DISCUSSION

In water of uniform depth periodic waves are propagated with uniform velocity and without change of form. The wave crests remain parallel to each other. This is demonstrated in Run 1 (Figure 3a). The relationship between period, length and velocity characteristics of periodic wave phenomena is

$$L = C\,T \qquad (1)$$

Where L is the length, C the velocity and T the period of the waves.

If water of constant depth is disturbed by small periodic impulses, the wave length and velocity are related to the depth by the equation

$$C = \sqrt{\frac{gL}{2\pi}\tanh\frac{2\pi d}{L}} \qquad (2)$$

where d is the water depth. As long as the surface tension has negligible influence and the wave height is small as compared with d and L, this equation applies to both deep-water and shallow-water waves.

For waves where surface tension is not negligible (where the radius of curvature is very small) the velocity is given by the equation

$$C = \sqrt{\left[\frac{gL}{2\pi} + \frac{2\tau\pi}{\rho L}\right]\tanh\frac{2\pi d}{L}} \qquad (3)$$

where τ is the surface tension in lbs/ft and ρ is the density of water in slugs/ft^3.

Experiments by A. J. Chinn (Reference 4), indicated that for wave lengths of 0.075 ft. or less, the effect of surface tension had to be considered, but that the second term ($2\tau\pi/\rho L$) in the velocity equation had to be modified. Chinn found that the average experimental results for waves in this region were 11.5% lower than indicated by the theory and in order to correct this discrepancy the term ($2\tau\pi/\rho L$) was reduced by 40%*. For the present ripple tank studies the

*The author of the present report is of the opinion that this statement should be viewed with caution and that additional laboratory experiments should be performed. This statement is based upon the results of a few measurements.

TABLE I

Data for the Ripple Tank Studies of the Motion of Surface Waves

Run No.	Description	Depth of water d (ft.)	Period of waves T (sec.)	Camera				
				focal length (mm)	f.	frames per sec.	camera above screen	screen above water
1	2	3	4	5	6	7	8	9
1.	Waves in water of uniform depth	0.04	0.24	15	1.5	64	6 ft.	34"
2.	Waves in water of different depth. There is an abrupt change of depth along the centerline of channel	d_1 0.071 d 0.027	0.22	15	1.5	32	6	
3.	Waves passing over an abrupt triangular shoal	d_1 0.036 d 0.020	0.187	15	1.5	48	6	47"
4.	Waves passing an abrupt triangular deep	d_1 0.04 d 0.03	0.24	15	1.5			
5.	Waves passing over an abrupt rectangular shoal	d_1 0.061 d 0.040	0.29	15	1.5	48	6	25"
6.	Waves refracting on a straight uniformly sloping beach. Slope 1:13 Angle between approaching waves and the beach . . . 57°	d_1 0.056	0.24	15	1.5	48	6	30"
7.	Waves entering a V-shaped straight channel with side slopes 1:12. Channel direction is the same as the direction of wave approach.	d_1 0.063	0.23	15	1.5	48	6	

TABLE I (Cont.)

Run. No.	Description	Depth of water d (ft.)	Period of waves T (sec.)	Camera				
				focal length (mm)	f.	frames per sec.	camera above screen	camera above water
1	2	3	4	5	6	7	8	9
8.	Waves diffracting from deep water into shallow water in shadow of a breakwater.	d_1 0.052 d 0.032	0.19	15	1.5	32	6 ft.	variable
9.	Waves diffracting from shallow water into deep water in shadow of a breakwater	d_1 0.032 d 0.052	0.19	15	1.5	32	6	variable
10.	Waves passing a breakwater oap	d 0.049	0.22	15	1.5	48	6	variable
11.	Waves reflecting off a vertical wall, inclined at 45° to the direction of the incident waves	d 0.090	0.19	15	1.5	48	6	40"
12.	Waves reflecting off a vertical walled wedge. Note diffraction at the other end of the wedge.	d 0.086	0.19	15	1.5	48	6	variable
13.	Waves going around a cone-shaped island (extending above the water level) with uniformly sloping beaches 1:15	d_1 0.045	0.18	15	1.5	48	6	varied
14.	Waves going around an island with irregularly sloping beaches			15	1.5	48	6	25"
15.	Waves going around a cylinder with vertical walls. Diam. of cylinder D...0.09 L, where L is the length of waves.	d_1 0.040	0.29	15	1.5	64	6	46"
16 to 25	All the same data but the diam. of the cylinder: 0.25L; for Run 16; Run 17 - 0.5L. Run 18 - 0.8 L. Run 19 - 1 L. Run 20 - 1.3L. Run 21 - 2.0L. Run 22 - 2.5L. Run 23 - 3.1 L. Run 24 - 3.25 L. Run 25 - 6.5L.							

wave length for each run was more than 0.075 ft., and in addition the surface tension was reduced to about 40 dynes/cm.; hence, the Equation (2) should be valid.

In Equation (2) tanh $(2\pi d/L)$ approaches unity when d becomes large as compared with L. When $d/L = 0.25$ the wave velocity is 5% less than that for deep-water waves. For $d/L = 0.5$, $\tanh (2\pi d/L) = 0.9963$ and the error in wave velocity will be negligible using the formula

$$C_o = \sqrt{\frac{gL_o}{2\pi}} = 5.12T \quad \ldots \quad (4)$$

where $\tanh (2\pi d/L)$ is taken as a unity. In most papers the waves in water having a depth greater than half the wave length are considered as deep-water waves, while waves in lesser depths are shallow-water waves.

If the wave length is very large as compared with the depth, $\tanh (2\pi d/L)$ approaches $2\pi d/L$ and Equation (2) takes the form

$$C = \sqrt{\frac{gL}{2\pi} \frac{2\pi d}{L}} = \sqrt{gd} \quad \ldots \quad (5)$$

Run 1 (Figure 3a) represents the condition for a uniform depth of water d = 0.04 ft. and a constant wave period T = 0.24 sec. To compute the wave length for the given condition we have from Equations (1) and (2) the following equation

$$L = g/2\pi T^2 \tanh (2\pi d/L) = 5.12\ T^2 \tanh h\ (2\pi d/L) \quad \ldots \quad (6)$$

In this equation L is in implicit form. To solve it, L in $\tanh (2\pi d/L)$ should be assumed for the first approximation and the computations repeated until the equation is satisfied. This procedure is tedious; consequently, tables have been prepared to present various factors as functions of d/L_o and d/L (Ref. 11).

Making use of Equations (1) and (4) it is found that

$$L_o = 5.12\ T^2 \quad \ldots \quad (7)$$

for Run 1 (Fig. 3a)

$$L_o = 5.12\ (0.24)^2 = 0.2949 \text{ ft.}$$

and

$$d/L_o = 0.1356$$

For this value of d/L_o in the tables it is found that $d/L = 0.1713$ which gives $L = 0.04/0.1713 = 0.234$ ft. This is in close agreement with the measured value of 0.24 ft.

For Run 2 (Figure 3a) the channel was divided longitudinally so that, starting from a certain point, half of the channel had a depth of $d_1 = 0.071$ ft. while the other half had a depth of d = 0.027 ft. The period was the same for both of the sections (T = 0.22 sec.).

$$L_o = 5.12\ (0.22)^2 = 0.2478$$

For the left side, d_1/L_0 = 0.2865. Making use of the tables (Ref. 11) it is found that d_1/L = 0.3000; hence, L = 0.071/0.3000 = 0.237 ft. as compared with the measured wave length, L = 0.24 ft. For the right side of the channel, d = 0.027, d/L_0 = 0.1090; hence d/L = 0.1488 and L = 0.027/0.1488 = 0.181 ft. which again was nearly the same as the measured value of 0.184 ft.

Wave Refraction

When waves approach a beach at an angle their crests are bent, because the in-shore portion of the wave front travels in shallower water and hence, at a lower velocity than does the portion in deeper water. The bottom topography, the wave period and direction of travel in deep water determine the characteristics of refraction in shoaling water. The result of refraction is a change in wave height, length and direction of wave travel. The lengths of waves travelling over a shoaling beach is decreased due to the decreased velocity for L = C T, as T remains constant. The decreased wave length means also a concentration of wave energy and, hence, an increase of wave heights, for

$$\frac{P_1}{P_2} = \left(\frac{H_1}{H_2}\right)^2$$

where P_1 and P_2 is the power per unit length of crest passing points 1 and 2 and H_1 and H_2 are the corresponding wave heights.

Thus, waves travelling over a submarine ridge usually will be decreased in length and increased in height and passing over a submarine valley will be increased in length and decreased in height.

To illustrate the refraction on a shoaling beach Run 6 (Figure 3a) was completed. A uniformly sloping beach with a slope of 1:13 was introduced with an angle of 57° between the front of approaching waves and the parallel contour-lines of the beach. The refraction pattern can be seen clearly in the photograph of Run 6. However, the best conception of this phenomena can be obtained by observing the moving pictures taken with a speed of 48 frames per second and then projecting them at about 1/3 of this speed. The increased heights of the waves on the shore are indicated by the sharper crest-lines in the photographs.

Runs 3, 4, and 5 (Figure 3a) illustrate the changes in wave lengths and velocities as the waves pass over shoals of various configurations. In Run 3 the waves are passing over an abrupt triangular shoal; in Run 5 over an abrupt rectangular shoal; while Run 4 demonstrates the wave characteristics when an abrupt "inverted" triangular shoal is introduced. It might be stated that Runs 3 and 5 represent the wave phenomenon over a submarine ridge, while Run 4 is similar to the wave characteristics over a submarine valley. Naturally the change of the depth in the ocean usually is not so abrupt. This will change the characteristics only as far as the angle of intersection of wave crest-lines is concerned. A gradual change of depth will introduce a gradual change in the direction of wave travel, as can be seen in Run 6, which demonstrates the refraction of waves on a sloping beach.

Run 7 (Figure 3b) was of wave refraction in a V-shaped channel with side-slopes of 1:12. It can be seen clearly that the waves "wheel" around by approximately 90° and break on the beaches as they enter the channel. The breaking waves are indicated by relatively wide and strong white lines in the photography. Almost all of the wave energy is destroyed in breaking waves, and so the wave height is decreasing very rapidly as they advance along the channel. From this relatively simple experiment it can be seen that it is advantageous to use a channel with flat sloping sandy beaches to connect a harbor or basin to a body of stormy waters in order to prevent the waves from penetrating into the harbor.

Wave Diffraction

When a wave train is interrupted by a breakwater or similar barrier a sheltered region is formed. The phenomenon by which water waves are propagated into this sheltered area is called diffraction. A knowledge of the diffraction phenomenon has important application in the design and location of breakwaters in connection with harbor development. It also has a bearing on the distribution of wave energy along beaches located in the lee of headlands and offshore islands. The phenomenon is analogous to the diffraction of light, sound and electromagnetic waves, and theories for breakwater diffraction have been adapted from those theories.

Basically there are two types of diffraction problems, connected with breakwaters:

(i) Diffraction around the end of a semi-infinite impermeable barrier.
(ii) The passage of waves through a breakwater gap.

No exact solution has been found for the case of a barrier of finite length, but it is believed that satisfactory results can be obtained by using the solution of semi-infinite barrier for each of the ends. It has been found that this assumption is allowable only in the case where the length of the barrier is long compared with the wave length (see also the section under "Islands").

The theory of water wave diffraction will not be presented here as this is readily available in the literature. The purpose of this paper is to demonstrate visually, by photographs and moving pictures, the wave-characteristics when diffraction occurs at various types of obstacles.

In Runs 8 and 9 (Figure 3b) a semi-infinite breakwater was introduced. Run 8 demonstrates the diffraction pattern from deep into shallow water around a breakwater tip. An abrupt change of depth was introduced along the geometrical shadow of the breakwater and the depth of the water in the shadow was about 3/5 of that outside. It can be seen that the wave-crests in the lee of breakwater are almost straight, up to a line drawn about 20° from the tip of the breakwater to the geometrical shadow. From here on the wave crest assumes an almost circular form, with the center at the tip of breakwater.

Run 9 (Figure 3b) demonstrates diffraction around a semi-infinite barrier, from shallow-water into deep water. The depth of water in the shadow section behind the breakwater is about 5/3 of that outside. As in the photographs, the height of diffracted waves in deep water is very small as compared with the incident waves. This is indicated by the wide, low contrast, crest-lines. The circular

oorm of the wave orest in the lee of breakwater is distorted again by a short, almost straight portion of crest, connecting the more advanced circular orest in deep-water and the incident wave in shallow water. The change from a straight crest to a curved one appears to be more abrupt than in Run 8. However, the diffraction pattern depends greatly upon the ratio of water depths in the lee of breakwater to the depths outside. For the uniform depth of water it would be expected that the wave crests in the shadow of the breakwater would assume an almost circular form, with their center at the tip of breakwater. As for the heights of diffracted waves - shallow water in the lee results in higher diffracted waves than if deep water exists in that area.

Some breakwaters have gaps through which vessels may enter sheltered waters. When waves pass through a gap, diffraction occurs at the two ends of the gap. In the case of a relatively narrow gap (compared with the wave length), the diffraction of waves in the lee of breakwater will be different than that around a semi-infinite breakwater tip. Theories have been developed for this condition (Ref. 3 and 10) and generalized diagrams developed by Johnson (6) for various conditions of wave approach and wave length. These diagrams can be used as transparent overlays, and by moving them over a chart of a harbor, the location of the breakwater to give the most desirable protection can be obtained.

It has been found that when the gap width is in excess of about five wave lengths, the diffraction patterns at each side of the opening are nearly independent of each other. In such cases the pattern given for a semi-infinite breakwater can be used to estimate the height and direction of waves on the leeward side. As a comparison, it might be mentioned here, that this fact seems to be valid also for the diffraction pattern around the ends of a finite-length breakwater. This has been demonstrated in Runs 15 to 25 (Figures 3f and 3g) wherein waves diffracted around a vertical walled cylinder. When the diameter of the cylinder approached 6 wave lengths, the diffraction patterns around each of the ends appear to be nearly independent as far as the alinement of the wave crests is concerned. This fact is discussed further in the section on "Islands".

Run 10 (Figure 3b) was made to demonstrate diffraction at a breakwater gap. A breakwater was introduced which extended completely across the tank, with an opening of about 1.2 wave lengths wide in its center. The water depth was uniform and the wave period was T = 0.22 sec. The nearly circular wave pattern, with center in the middle of the gap, canbe observed in the photograph. The change of wave heights is indicated by the intensity of white crest-lines. The waves were relatively high close to the gap and along a line parallel to the direction of wave approach and passing through the center of the gap. The wave height decreased rapidly within the shadow of the breakwater in the direction perpendicular to the direction of wave advance, and less rapidly in direction of wave approach.

It has been shown by Putnam and Arthur (Ref. 2) that the geometrical shape of the breakwater tip, within the limits of their investigation, had no material influence on the wave diffraction pattern. With a sharp corner, it was observed that a secondary disturbance originated at the corners with propagated capillary waves with a circular pattern superposed upon the main gravity-wave system. This is very clearly demonstrated in Run 10 (Figure 3b). A better conception of this phenomenon can be obtained by observing the movies of this run; however, the pattern can be distinguished also in the photo shown in

Figure 3b. Rounding of the corners will practically eliminate the secondary capillary wave system. This is demonstrated in Run 12 (Figure 3b) wherein diffraction occurs around the leeward end of a vertical-walled wedge.

Wave Reflection

Wave motion in harbor basins often is increased due to waves being reflected from vertical or nearly vertical walls. In small-scale models involving wave action the side walls and wave generator of the models or tanks may result in reflections which can produce erroneous or misleading results. Total reflection will occur at smooth vertical, rigid, impermeable barriers, while for almost total dissipation a flat sloped permeable wall is necessary. There is a transition region between total reflection and total dissipation. Besides the slope of the wall and the characteristics of its construction (rigidity, permeability, roughness of the surface etc.) the following factors effect the dissipation of wave energy: (i) the water depth, (ii) the wave length, (iii) the wave height, (iv) the angle of wave approach.

Runs 11 and 12 (Fig. 3b) were made to demonstrate the reflection of gravity water waves at a rigid, vertical-walled barrier. In Run 11 a barrier was introduce at 45° to the direction of wave approach, while in Run 12 a quarter of a cylinder was used with the tip of the wedge facing the approaching waves and the sides of the wedge inclined by 45° to this direction. The depth of the water was uniform for both of the runs. From the few experiments performed it appears that (i) the angle of incidence was equal to the angle of reflection; (ii) the wave lengths and velocities remain unchanged - only the direction of travel being changed; (iii) in case of a smooth, rigid impermeable vertical wall, the individual wave heights were not greatly affected by the reflection.

Conclusions (i) and (ii) are verified by the fact that the incident waves and reflected waves formed almost perfect squares when the angle of incidence was 45°, as can be readily seen in the photographs of both Run 11 and Run 12 (Figure 3b). The third conclusion came from the fact that the intensity of white crest-lines of reflected waves close to the obstacle was almost the same as the intensity of the incident waves (see Run 11).

Runs 15 to 25 (Figures 3f and 3g) also show reflection patterns, where the pattern of reflected waves appear to be circular. Total reflection may result in doubled wave heights due to the superposition of incidence and reflected waves. This is demonstrated in Run 11 (Figure 3b) by the high intensity of the intersections of incidence and reflected wave trains. An engineer, designing a harbor should take this fact under consideration. Breakwaters to be built close to navigation channel should be constructed so as to absorb all or most of the wave energy without considerable reflection. There are many harbors where this fact was not taken into consideration; the result being that the entrances to the harbors are dangerous to navigation, even for incident waves of medium height.

Islands

When a train of waves is interrupted by an island, there is generally a zone of "wave shadow" in the lee of the island. Since the regular pattern of a long swell is disturbed even at great distances beyond islands, the early navigators were able to use this phenomenon as a guide to new islands. The factors which

influence the penetration of wave energy into the wave lee of an island are: (i) refraction by underwater topography, (ii) refraction by currents, (iii) diffraction, (iv) variability in direction of wave travel. These factors may be closely related.

Refraction by underwater topography. The distribution of refracted wave energy in the lee of an island is critically dependent upon the bottom slope. When the wave approaches the shore, its velocity will be reduced due to the decreasing depth of the water; and when the crests reach the beach they tend to become parallel to the shoreline, regardless of their direction of approach from deep water. The waves "wheel" around and break nearly at right angles to the beach.

In Run 13 (Figure 3b) a transparent cone-shaped island was introduced, with uniformly sloping beaches extending above the water level. The slope of the beach was 1:15 (see data in Table I). One can see clearly the refraction of the waves on the beach: the widening of the crest-lines in the pictures indicates the increase in wave heights toward the shore due to the convergence of energy along the crest.

Refraction by currents. The wave characteristics such as steepness, length and direction of travel will be changed when waves encounter currents. (i) The steepnesses of waves meeting opposing currents increases, and when the current is strong enough the waves might break. (ii) The wave steepnesses will be reduced by a current in direction of the wave travel. (iii) When waves meet a current at an angle, directional changes occur in wave travel.

In these idealized ripple-tank studies no currents were present. The usual semipermanent currents around islands is not significant because of low current velocities involved. However, tidal currents around the islands may be strong enough to cause important refraction effects.

Diffraction of waves around the islands. Wave energy is also propagated into the lee of an island by diffraction, as well as by refraction. The effect of such diffraction was estimated by Putnam and Arthur (Ref. 2). They utilized the theory of diffraction of waves by a semi-infinite plane barrier in water of uniform depth as introduced by Penny and Price (Ref. 9). This theory does not apply for small islands, but the results appear to be useful in the case of large islands (many wave lengths in diameter). This is illustrated by comparing the results of runs 15 to 25 (Figs. 3f and 3g) where a wave-train is interrupted by a cylinder with the axes perpendicular to the water surface and with the cylinder diameter varying from 0.09 L to 6.5 L. It appears that very small cylinders have almost no effect upon the wave train (Run 15, D = 0.09 L). For the cylinders with D = 0.8 L the effect of the cylinder was apparent to a distance of approximately 3 wave lengths in the lee of the cylinder. This distance increased with increasing cylinder diameter, until at D = 3.1 L (Run 23, Figure 3g) nearly circular waves passed around the cylinder without interference effects in the lee. This phenomenon takes a relatively definite configuration at a distance of approximately D = 6 L. Hence, it appears that the theory of diffraction of waves around a semi-infinite breakwater tip might be used for islands larger than 6 wave lengths (which compared with diffraction at a breakwater gap). However, more experiments are necessary before more definite conclusions can be stated.

Variability in direction of wave travel. The extent of the sheltered region in the lee of an island depends largely upon the variability in direction of travel of the incident waves. Larger variability means an increase in wave intensity in the sheltered area.

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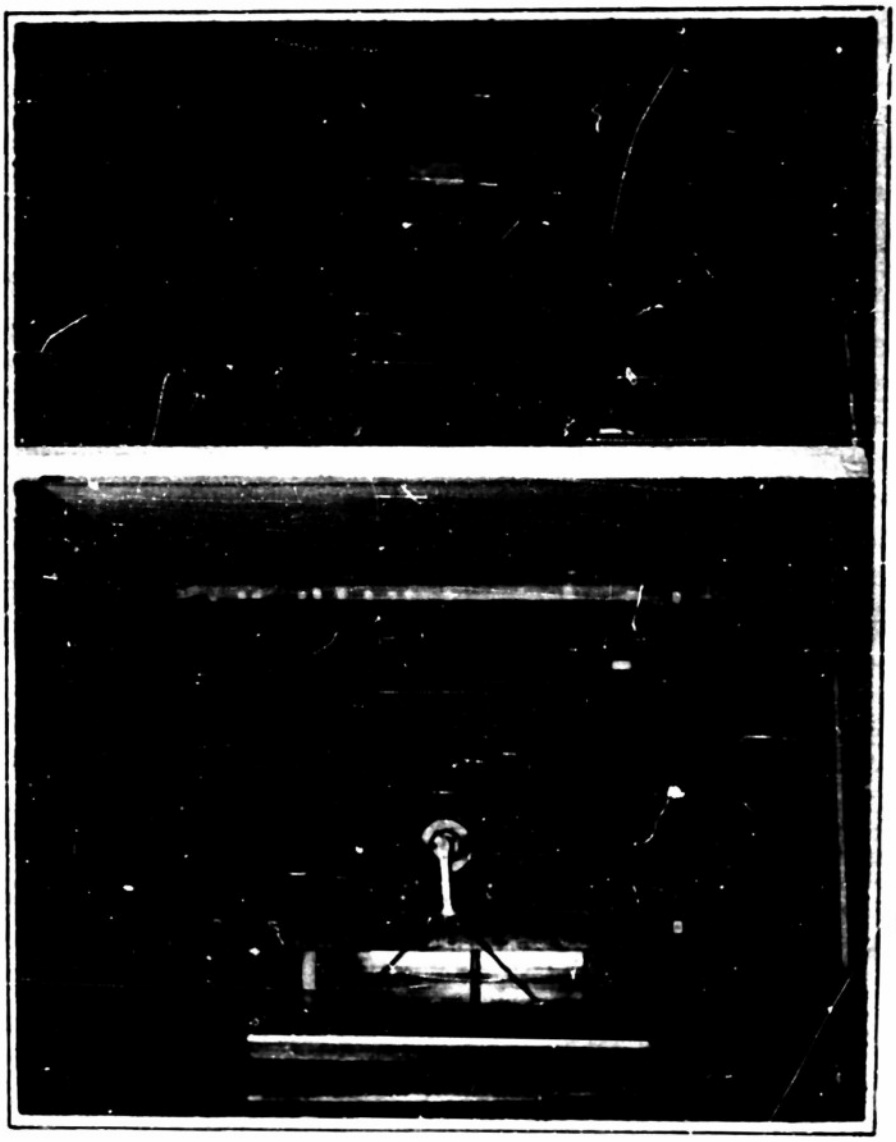


FIGURE 1 - GENERAL VIEW OF EQUIPMENT

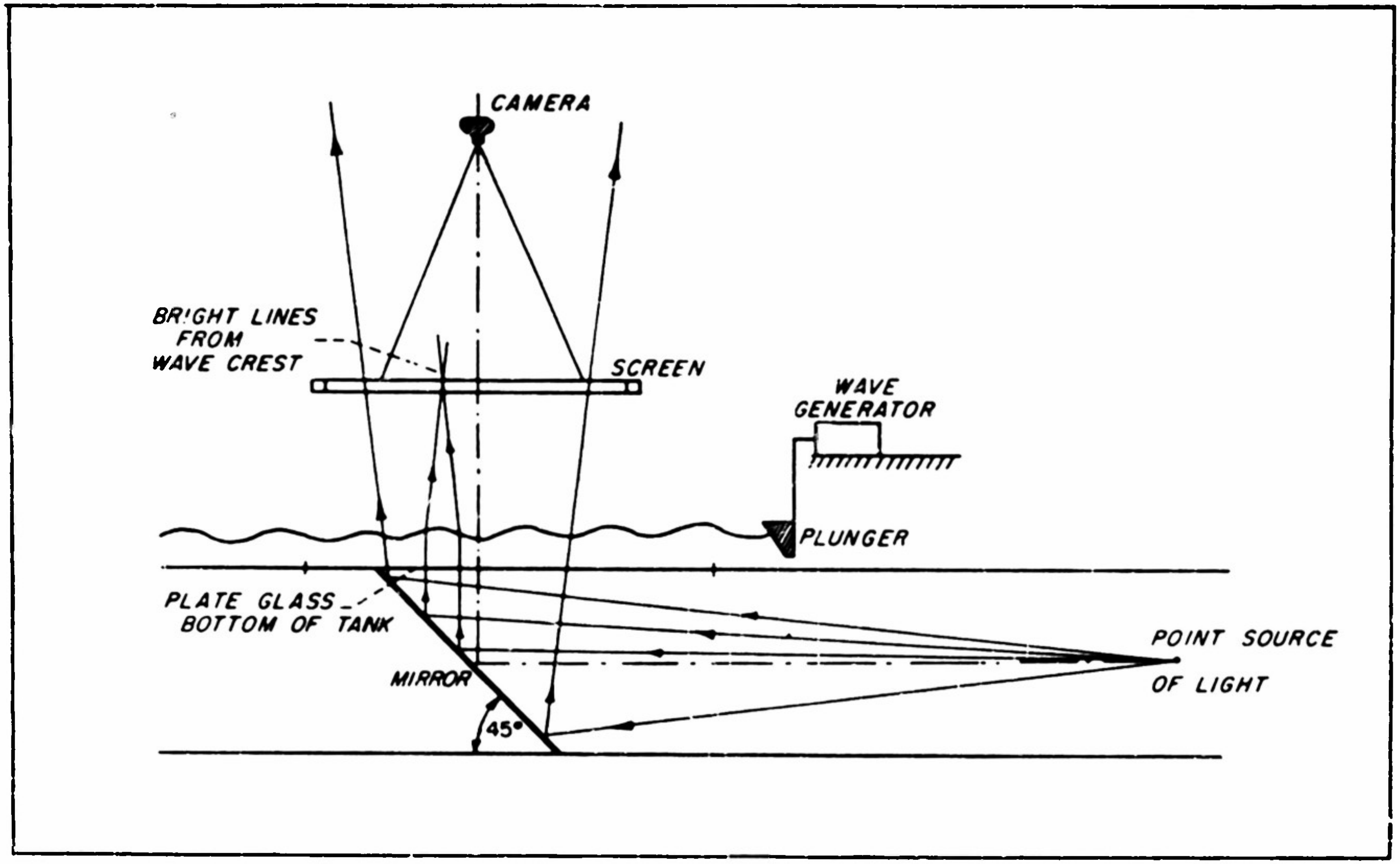
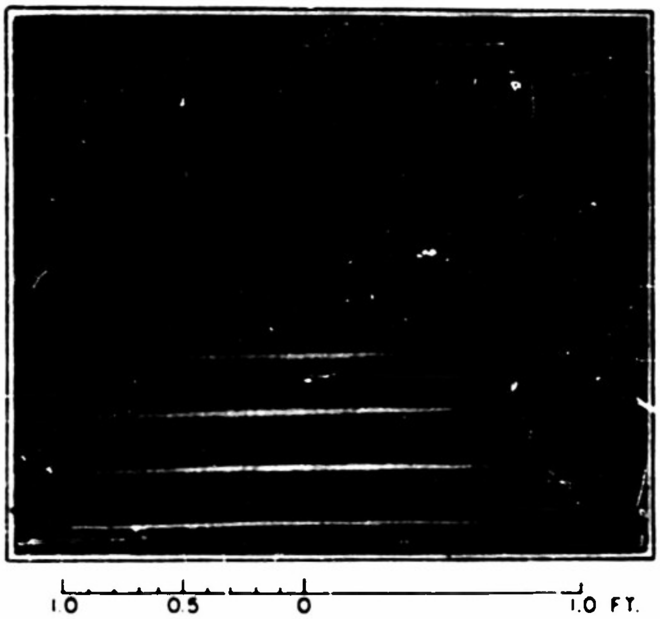
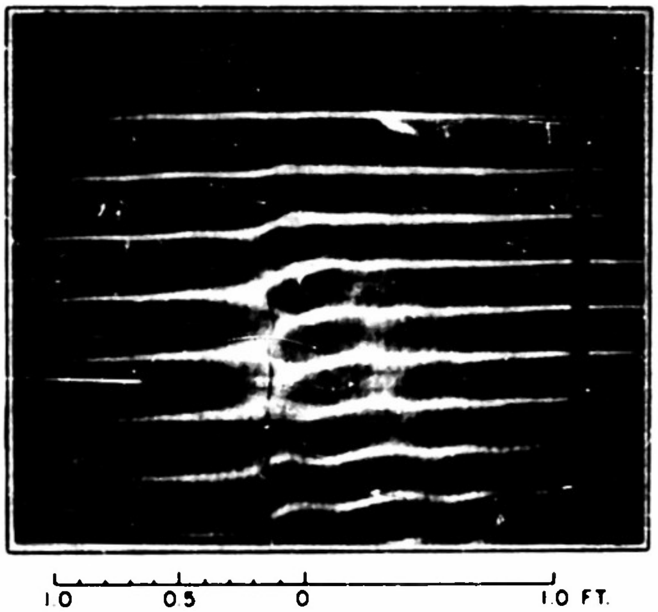


FIGURE 2 - SKETCH OF THE EQUIPMENT



RUN 1



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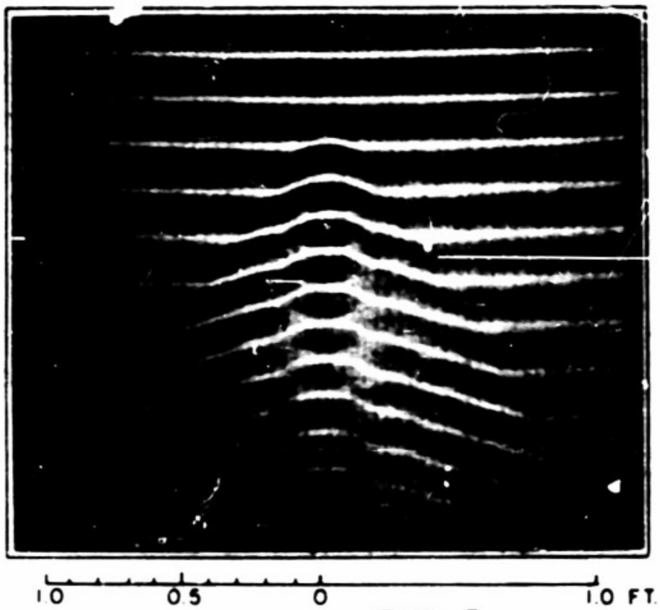

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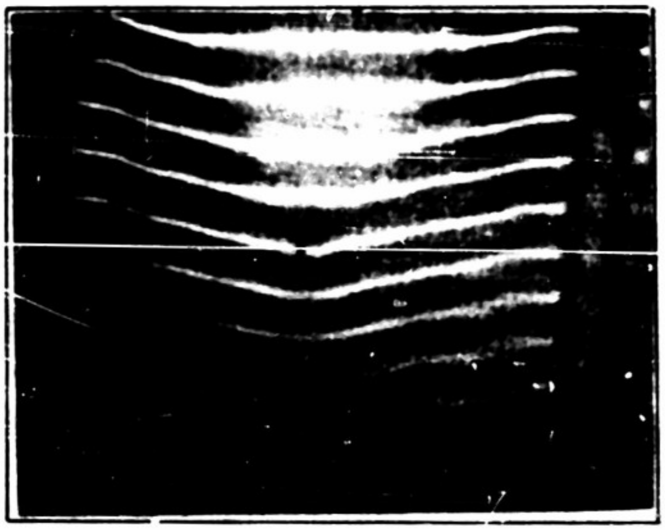

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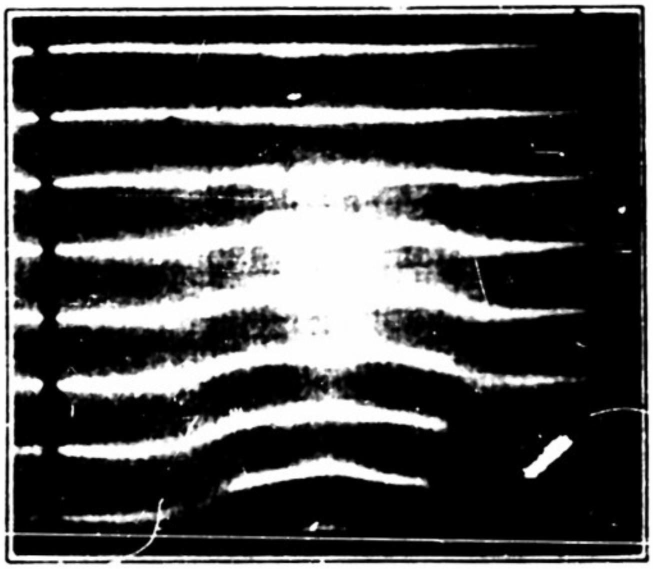

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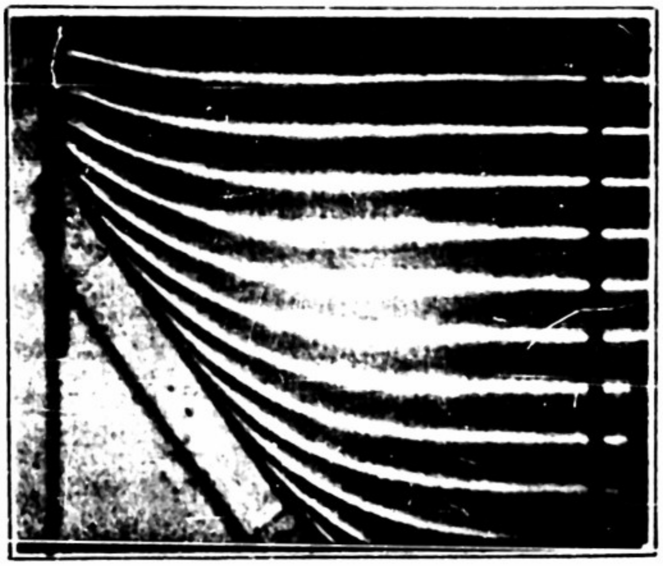
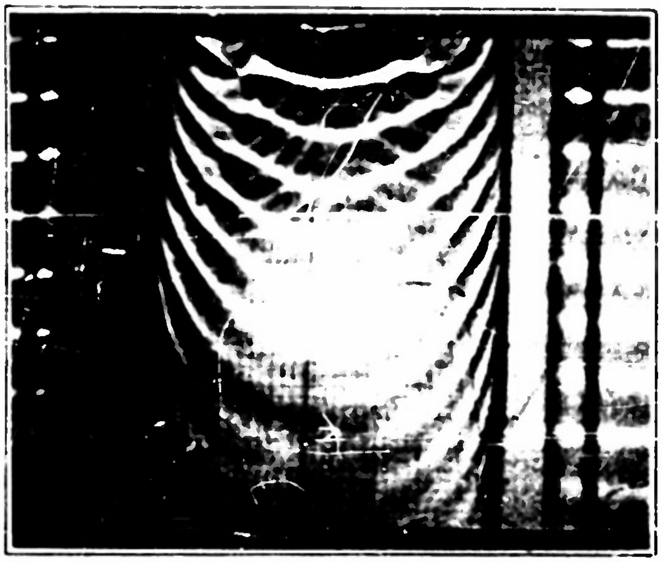


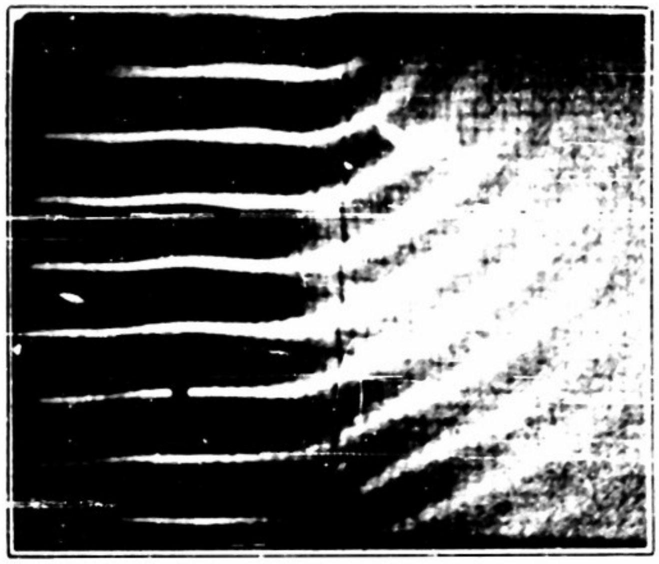
RUN 6

For data see Table I

FIGURE 3a



RUN 7



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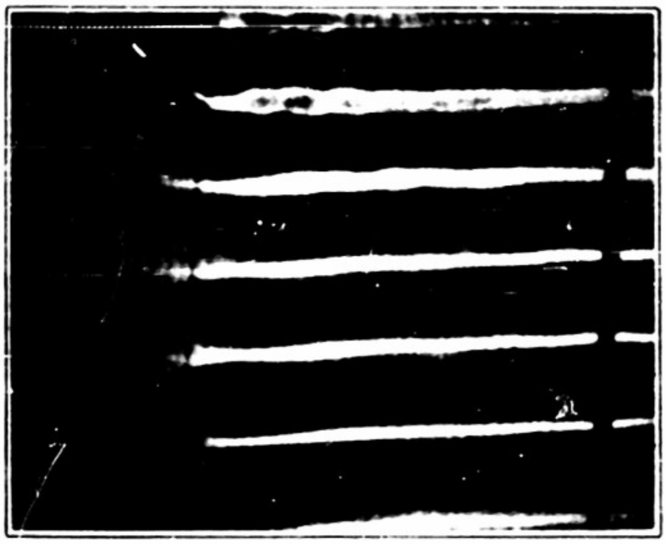

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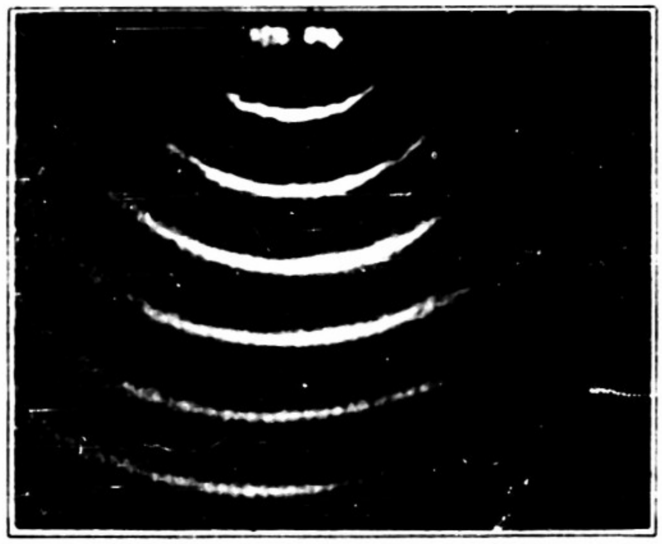

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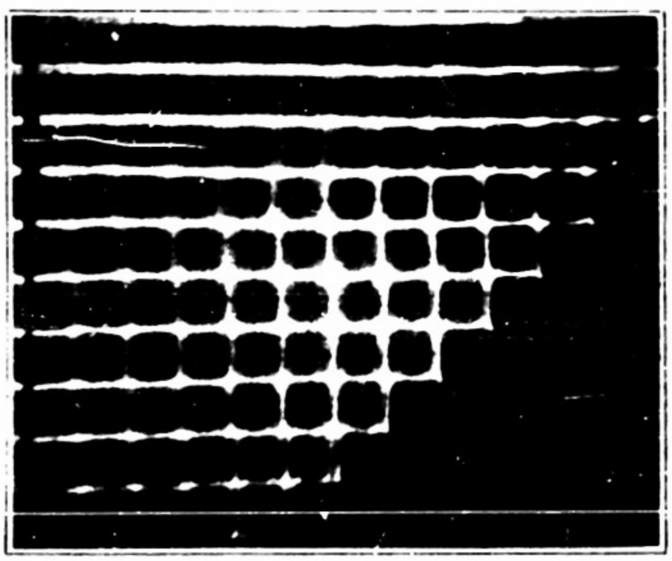

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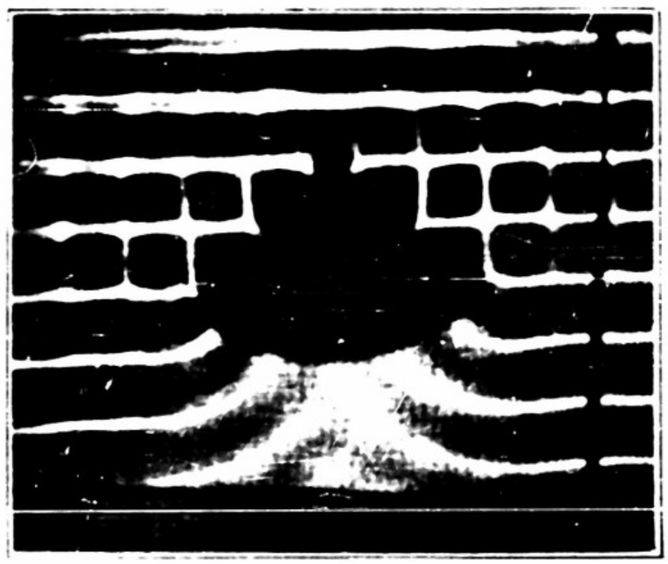
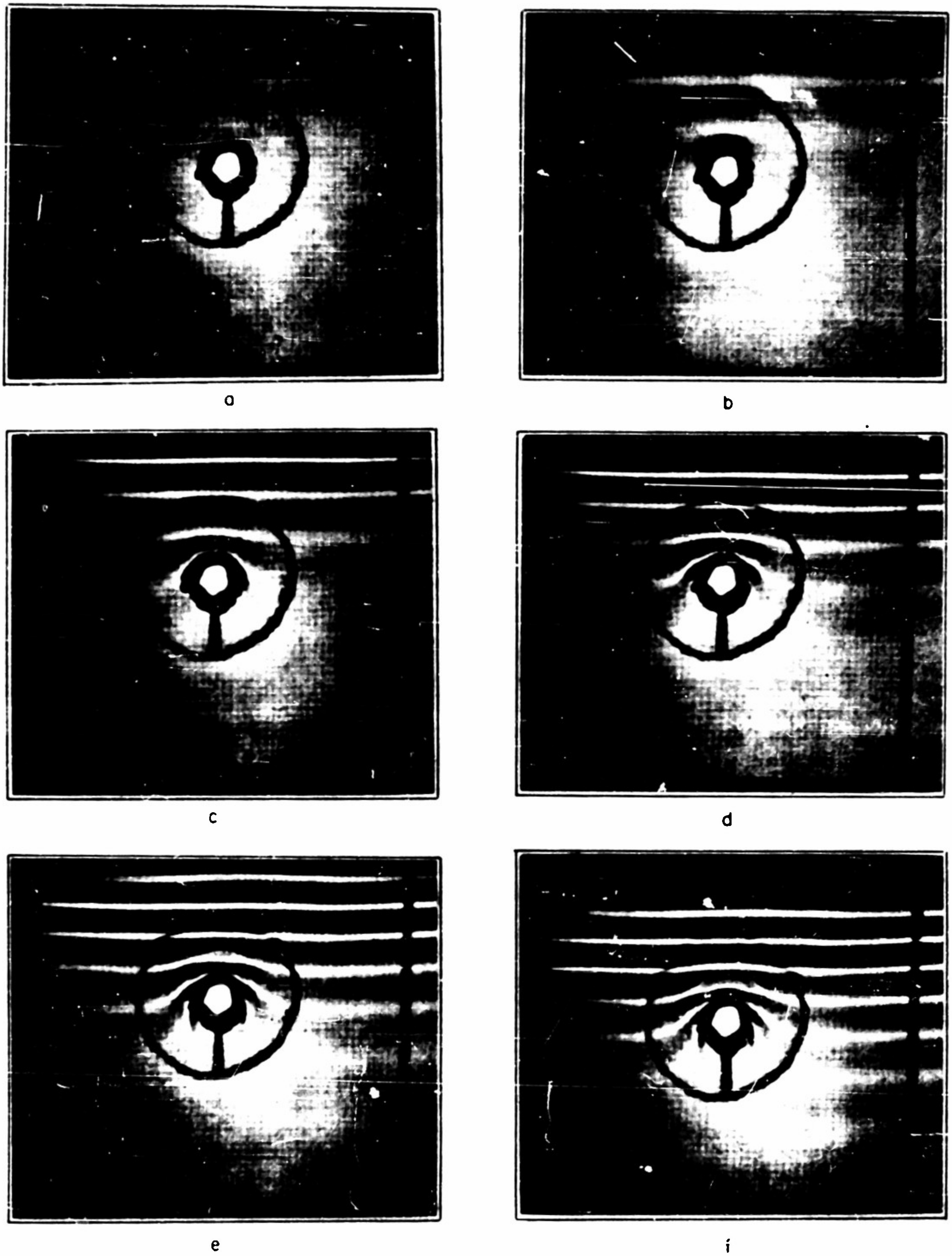


RUN 12

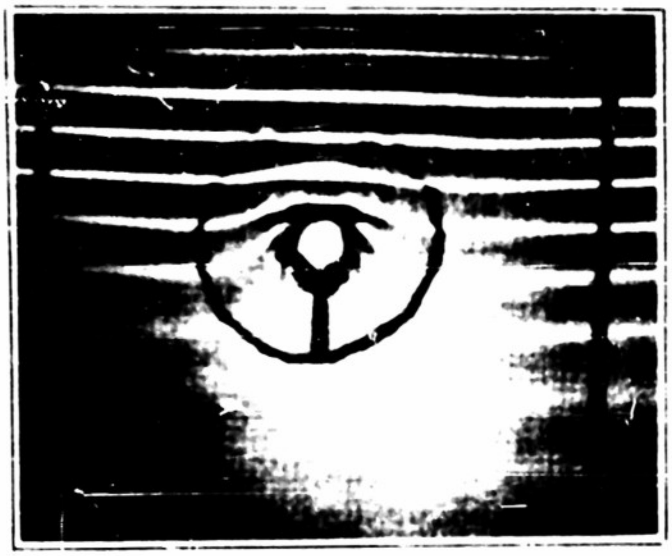
FIGURE 3B



RUN 13

Photos a to k taken at intervals of 0.25 second

FIGURE 3c



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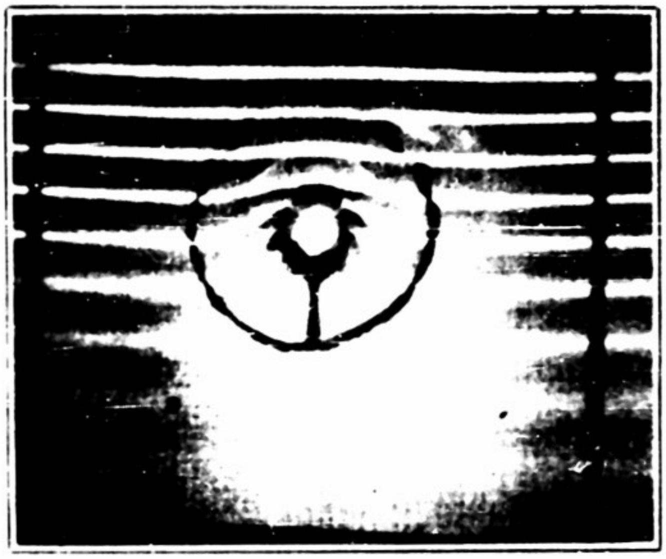

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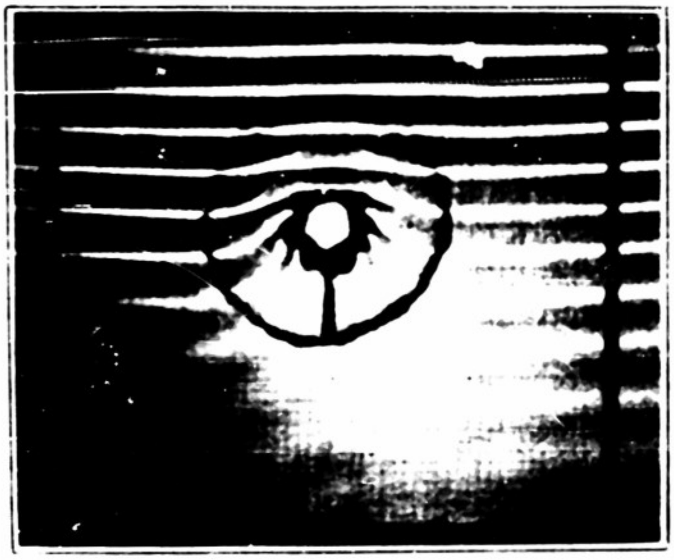

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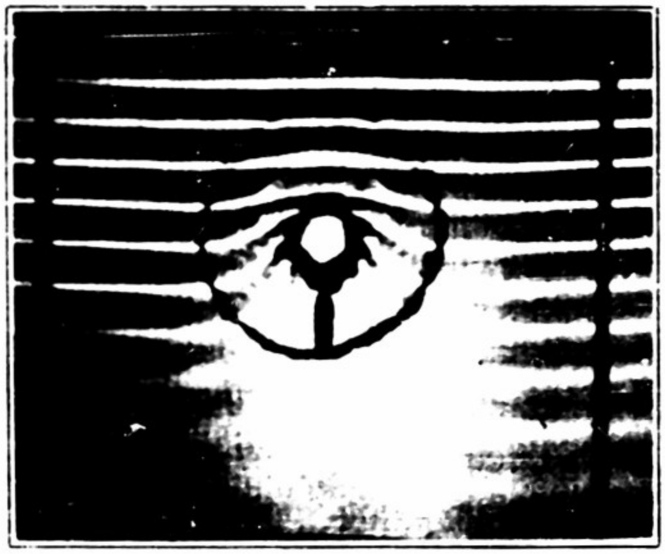

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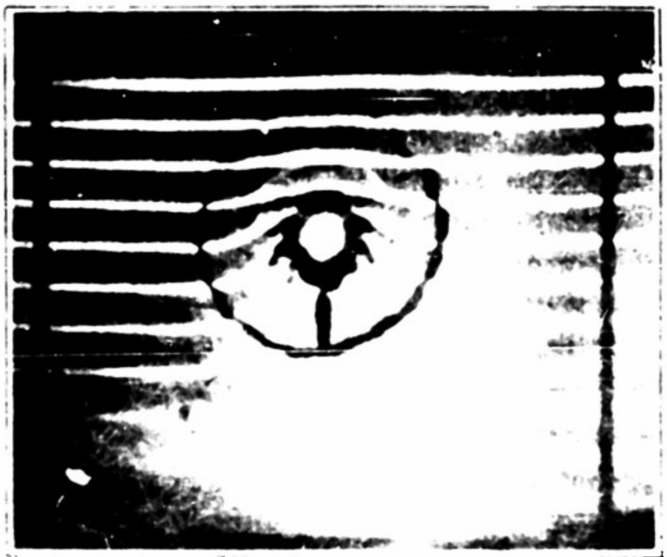
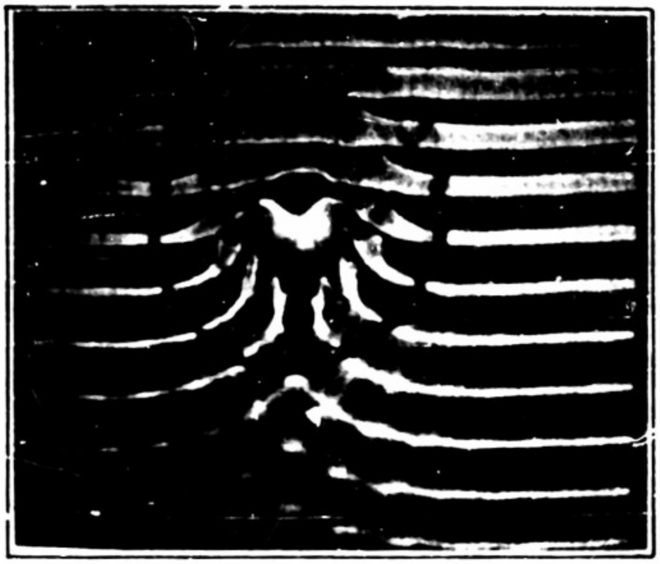


k

RUN 13 (cont.)

FIGURE 3d



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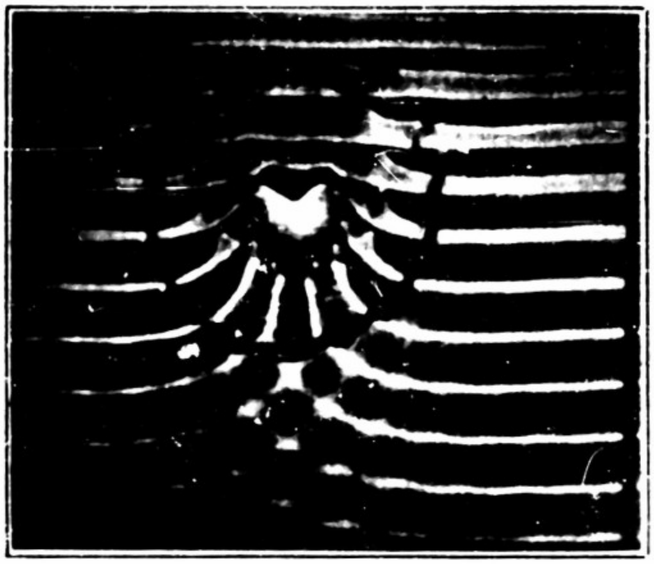

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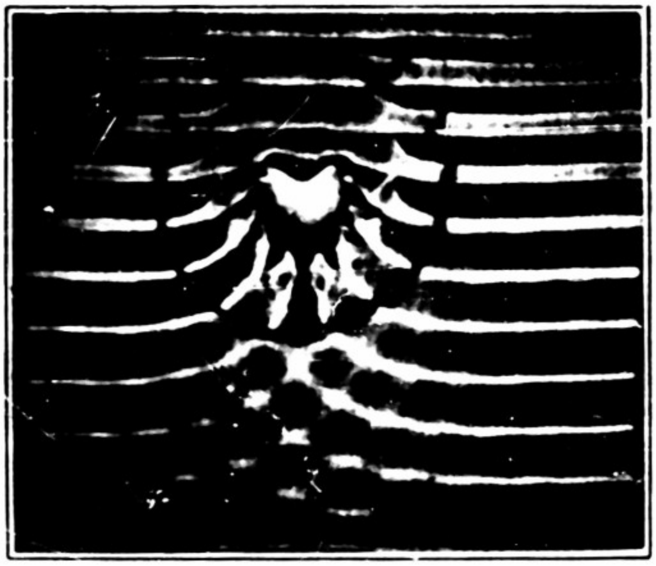

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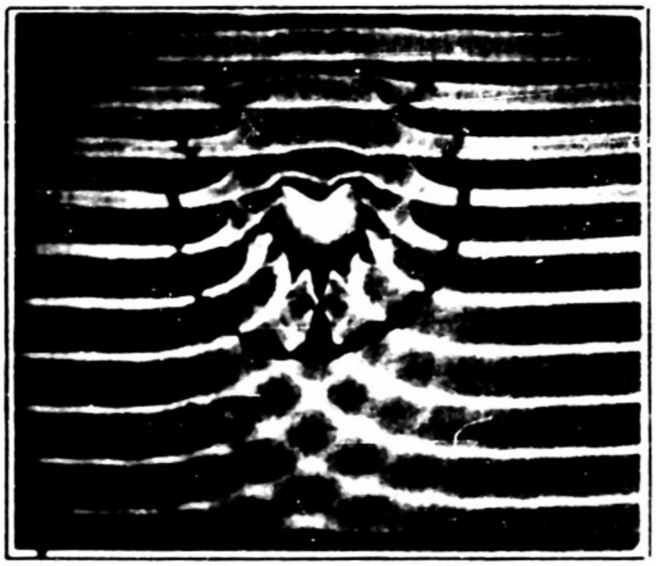
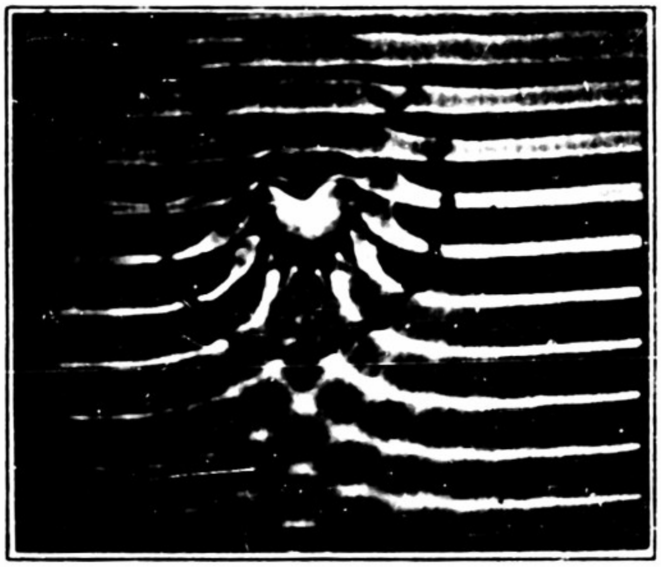


o



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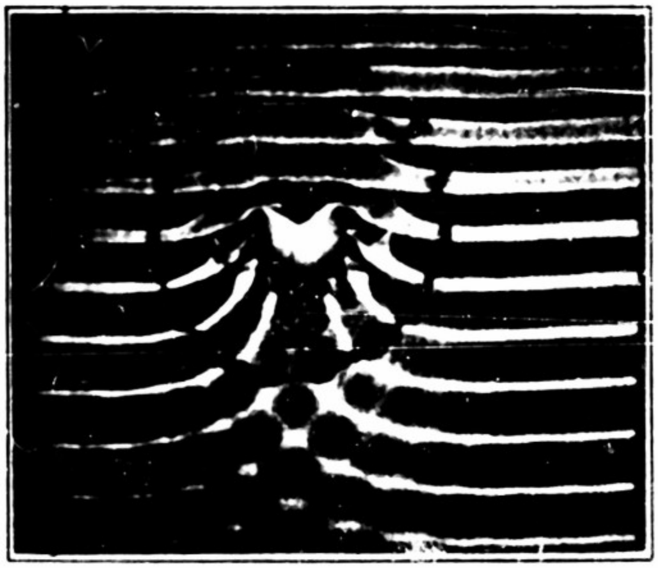
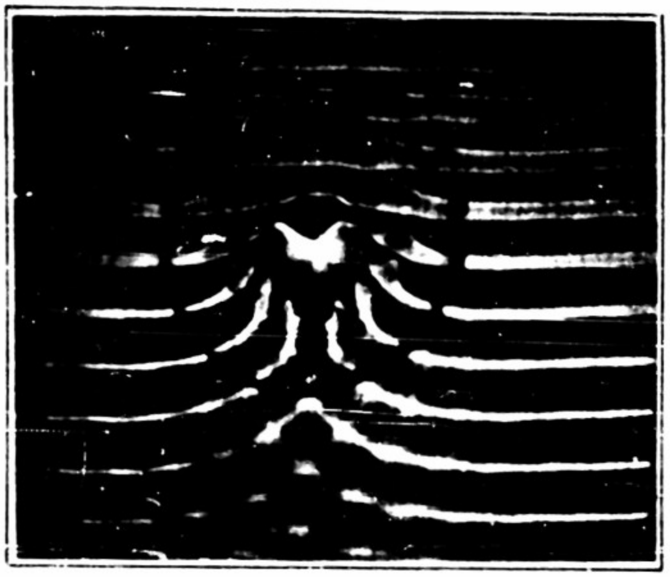


q

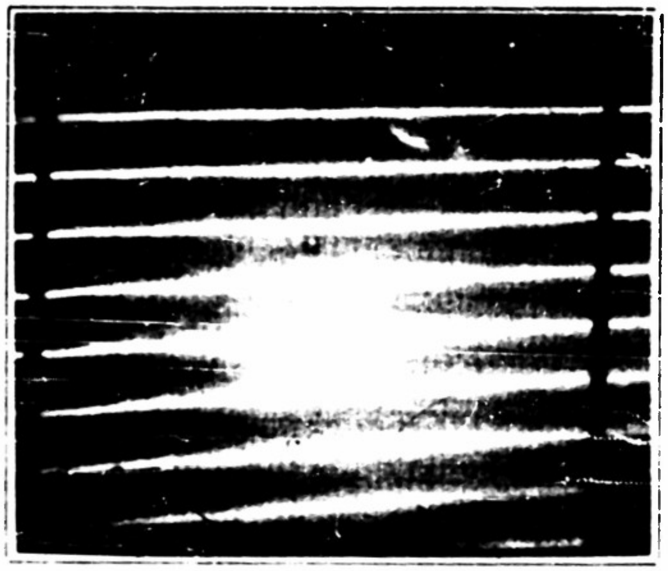
RUN 13 (cont.)

Photos l to r taken at an interval of 0.02 second

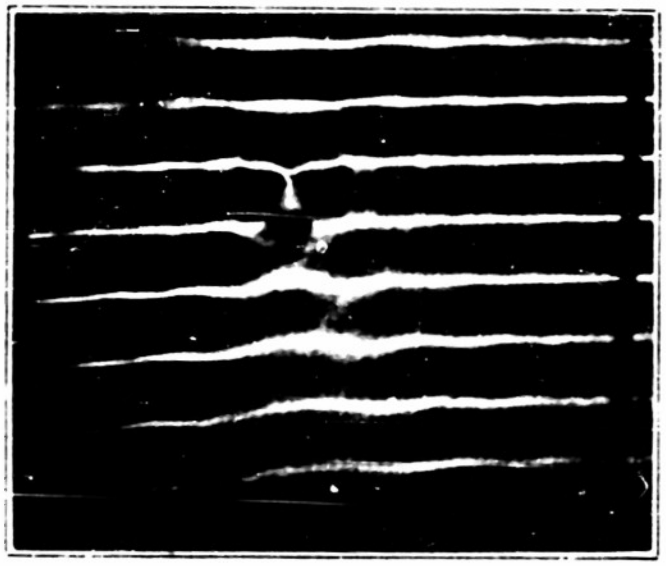
FIGURE 3e



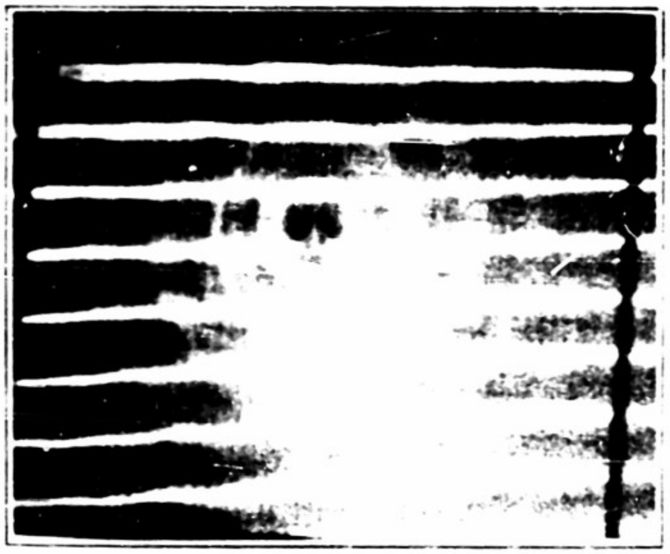
RUN 13r



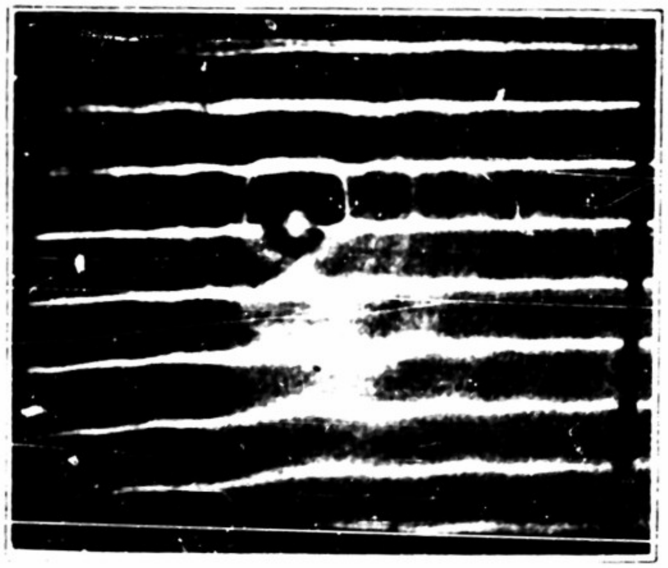
RUN 15



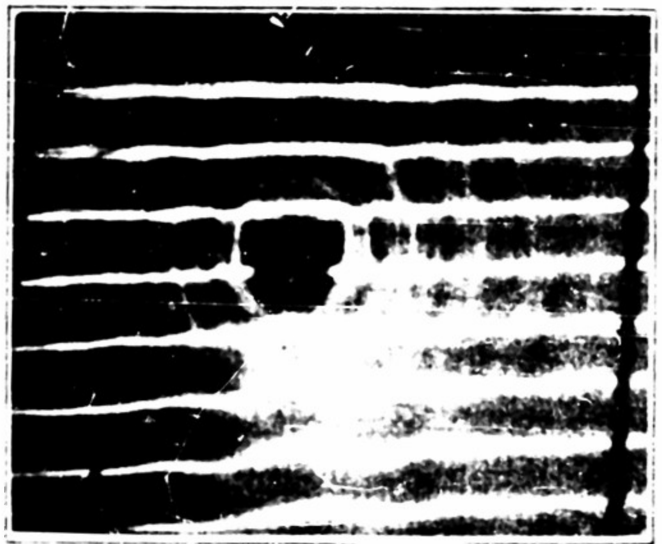
RUN 16



RUN 17

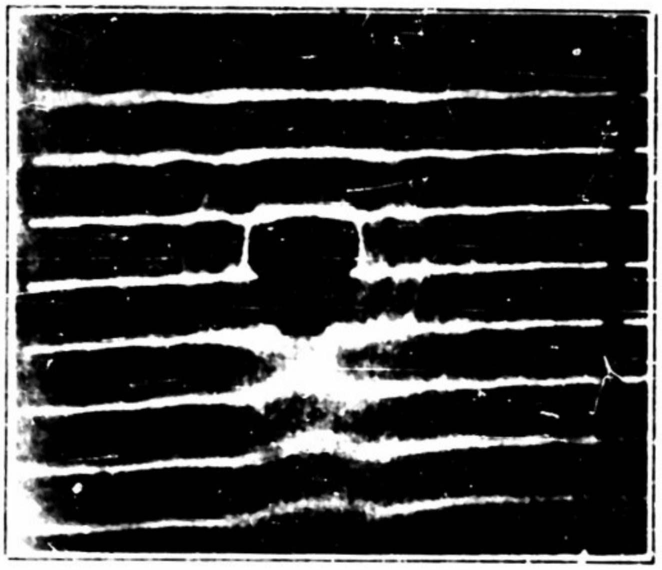


RUN 18

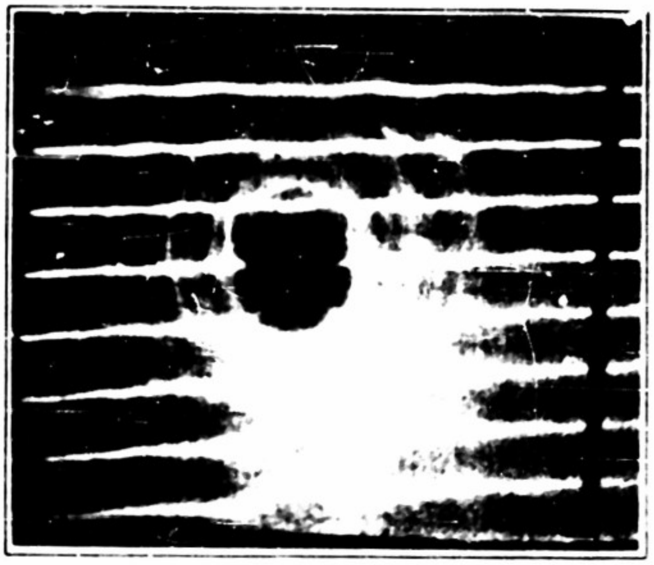


RUN 19

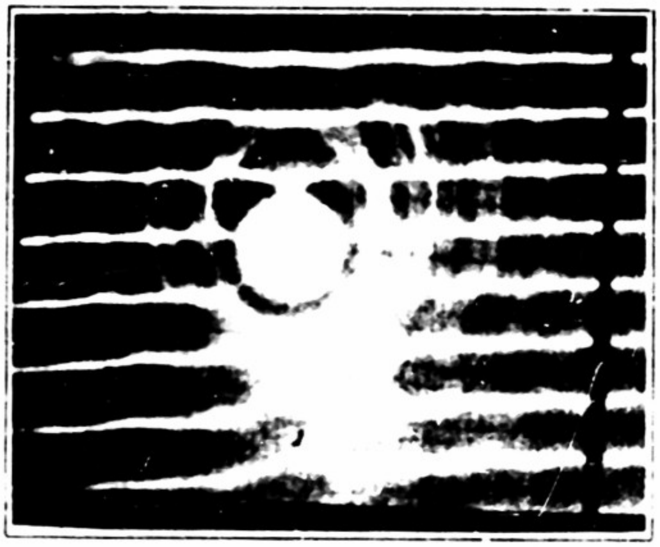
FIGURE 31



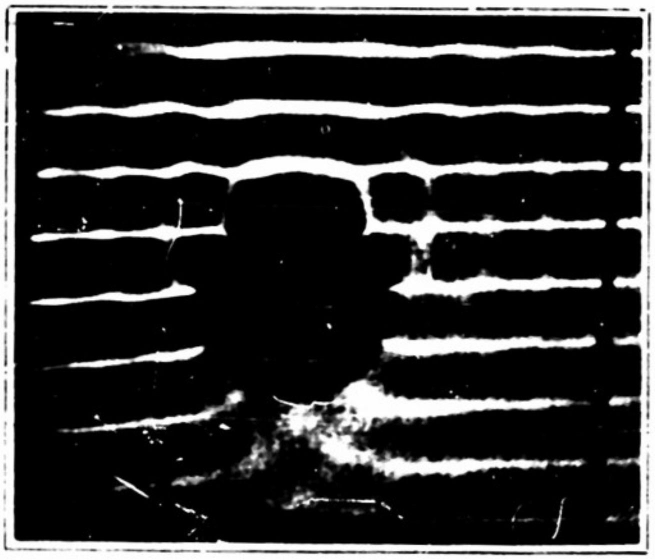
RUN 20



RUN 21



RUN 22



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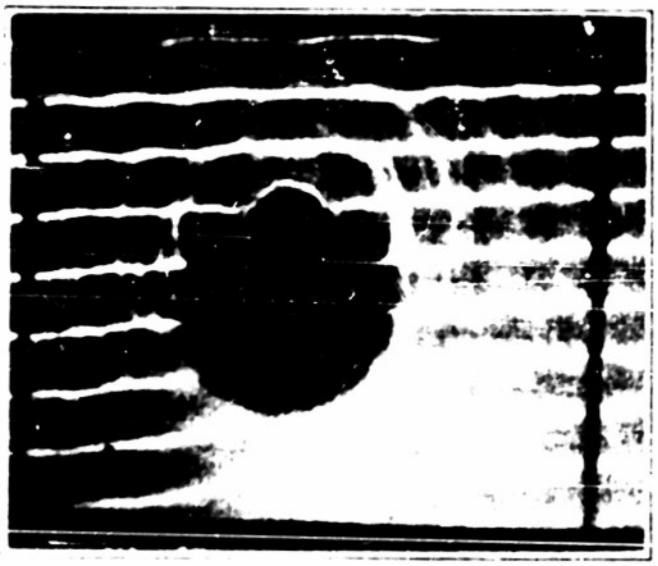
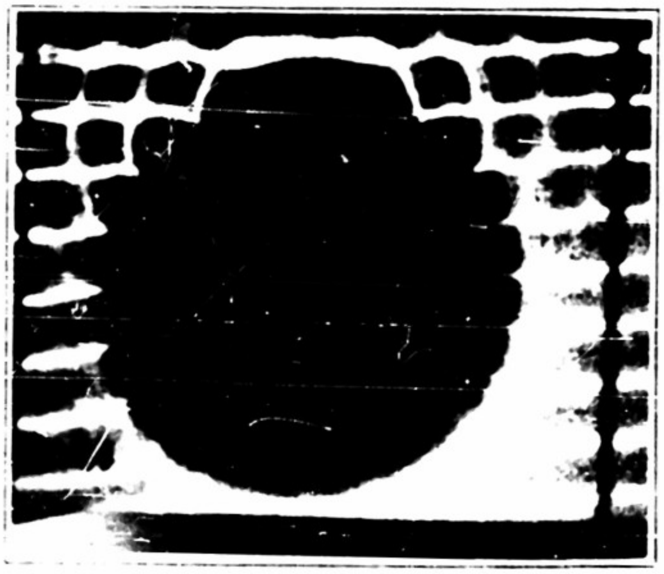


RUN 24



RUN 25

FIGURE 3g

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